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THE ROLE OF FLUORINE IN THE DIET

By RUTH WOODS

In Newburgh, New York about fifty-one pounds of sodium fluoride—a highly toxic chemical—are added daily to the public water supply. Dissolved in the three million gallons of water used daily for all purposes in Newburgh, this amounts to about one part per million or less of fluorine in the water. This practice has been in effect for three years and will continue for another seven. Far from feeling any apprehension, the 30,000 inhabitants of this city consider themselves exceptionally fortunate. They are participating in a scientifically controlled experiment demonstrating the ability of fluorine, in trace amounts, to reduce the incidence of the most common disease of civilized man—dental caries.

The Fluorine-Dental Caries Relationship:

That fluorine in concentrations of one part per million in domestic water supplies substantially decreases the incidence of dental caries has been established beyond question by epidemiological surveys in areas where such concentrations naturally exist. Similar surveys have revealed a high incidence of caries among inhabitants in areas whose water supply is substantially fluorine-free. On the other hand, persons living in areas where the natural fluorine content of the water exceeds one part per million regularly exhibit marked toxic effects, most common of which is the disfiguring dental defect known as "mottled enamel." Analytical comparisons between carious and non-carious teeth as well as biological experiments with laboratory animals have further confirmed the conclusions drawn from epidemiological public health surveys with respect to the role of fluorine in dental health.*

The Newburgh experiment, together with several similar ones in at least six other cities in the United States and one in Canada, represents the first attempt to prove the fluorine-dental caries relationship by direct experimental methods. For the first time fluorine is being *added* to waters normally nearly fluorine-free in an attempt to reproduce conditions observed in areas where the water naturally provides optimal amounts of this element. As a further check on the results obtained for each city participating in this experiment there is a control city—a nearby city comparable in all respects (water-supply, population groups, climatic conditions, economic status and common sources of food supply), except that its water supply is fluorine-free.

The nature of the fluorine-dental caries relationship is such that the effects of fluorine ingestion are exerted to a maximum degree on teeth in

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**cf. Borden's Review of Nutrition Research,* December, 1942 "Fluorine and Dental Health."

the formative stage, before final calcification and deposition of enamel are complete. This means that maximum fluorine inhibition of dental decay by dietary means can be effected only in children during the first eight to ten years of life. For this reason, full evaluation of the fortification of public water supplies with fluorine cannot be made until completion of the ten-year experimental period. As the experiment progresses, even in the early stages results appear so promising that a review of the history and progress of the study seems highly desirable. The relatively new discovery that even mature, adult teeth may be protected against the development of new cavities by topical application of a concentrated fluoride solution directly to the teeth constitutes another chapter in the story of fluorine and dental health.*

Concerning the fortification of communal water supplies with fluorine as a mass experiment on the role of dietary fluorine in dental health, McKay (1) has commented:

> "When a vision appears it remains only that, until some far-seeing individual recognizing the reality, translates it into accomplishment. It is a noteworthy achievement to marshall the facts and evidence, and convincingly present them to the responsible officials of a community, as was done in Newburgh, N. Y. There might have been much objection to adding fluoride to a communal water supply pending demonstration that it can be done without causing toxic effects. The removal of fluorine from water for the prevention of one defect *(mottled enamel)*, and its addition for the prevention of another totally different lesion *(dental caries)*, is one of the most curious reversals in the whole history of science, and is certainly without precedent in dental history. It is wholly a question of amount whether the influence of fluorine is good or bad."

Mottled Enamel vs. Dental Caries:

The discovery of fluorine as a prophylactic agent against the development of dental caries arose most unexpectedly as a result of investigations begun about forty years ago on the nature and cause of mottled enamel. This peculiar dental condition consisted of mottling of the tooth enamel with white, chalky patches and discolorations ranging from yellow to dark brown. Often whole towns were afflicted, so that the condition was not considered unusual until the children grew up and left the community. Smith (2) reports the difficulties encountered particularly by girls from such communities in seeking employment, the prospective employers usually suspecting them of being secretly addicted to snuff.

The fascinating story of how the phenomenon of mottled enamel was traced to the water supply and how twenty-five years elapsed before scientific

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*Because the topical application of fluorides cannot be considered a nutritional problem, it will not be discussed in the present Review.

methods were sufficiently advanced to reveal traces of fluorine as the causative agent in the condemned water sources has been told in detail (3, 4, 5, 6, 7, 8) in an earlier issue of this Review. In that same issue it was revealed how the realization gradually developed that an unusual relation existed between mottled enamel and the incidence of dental caries. Results of numerous surveys disclosed the striking fact that the teeth of individuals with the mottled enamel defect were remarkably free from the usual dental decay observed in non-afflicted areas (9). It soon became apparent that not only were mottled teeth less susceptible to decay, but such teeth actively resisted decay.

With the recognition of fluorine as the causative agent in the development of mottled enamel, now identified as *dental fluorosis,* work was directed toward correlation of fluorine intake, development of mottled enamel and the incidence of dental caries. Epidemiological surveys throughout the United States (Table 1, page 4) begun in 1938 by the United States Public Health Service and continuing for about four years (10, 11, 12, 13, 14, 15, 16) established what is now known as the "fluorine-dental caries hypothesis."

This hypothesis states that the constant use, during the stages of permanent tooth development, of a water supply which contains fluorine in a concentration of one part per million exerts a definite protective effect against the development of dental caries. Waters containing fluorine in excess of this amount tend to cause dental fluorosis (mottling of the enamel), while waters containing less than 1 p.p.m. or none, are without caries-inhibiting value.

The fluorine-dental caries hypothesis has been substantiated not only by repeated epidemiological surveys but by biological experiments with laboratory animals and by the findings of analytical studies on the variations in fluorine content between normal and carious teeth. The present paper will review the newer findings in this field since 1942.

New Fluorine Studies:

Since 1942, studies on the role of fluorine in dental health have increased rapidly, not only in the United States but in Canada, the British Isles, India (17) and South Africa (18) as well. Without exception, the findings of all these investigations have confirmed the statements of the original fluorine-dental caries hypothesis. Certain aspects of the fluorine problem, however, still remain unanswered or the subject of controversy. These include, for example, the mechanism of the protection afforded by fluorine; the expected quantitative response in a given community exposed to controlled fluorination of the water; the effect of fluorine on teeth which have

TABLE 1

Summary of dental-caries findings in 7257 selected, white, school children, age 12 to 14 years, in 21 cities of 4 states in relation to the fluoride (F) content of the public water-supply

City and State	CLINICAL DATA					WATER DATA			
	Number of children examined	*Percent of children examined,[1] with oral L. acidophilus in saliva; number per cc.*		*Percent of children examined, caries free*	*Number of permanent teeth per child, with dental-caries experience (DMF)*	*Fluoride (F) concentration, of public water-supply, in ppm.*	*Total hardness, in ppm.*	*Source*
		Neg. and < 100	*30,000 and >*					
Galesburg, Ill.	273	.....	.....	27.8	2.36		247	Deep wells
Colorado Springs, Colo.	404	.....	.....	28.5	2.46 } 2.44	> 1.4 { 2.6	27	Surface (Pike's Peak)
Elmhurst, Ill.	170	35.7	24.7	25.3	2.52		323	Deep wells
Maywood, Ill.	171	39.6	20.9	29.8	2.58		75	Deep wells
Aurora, Ill.	633	38.2	25.6	23.5	2.81		329	Deep wells
East Moline, Ill.	152	.....	.....	20.4	3.03 } 2.94	1.0-1.4 { 1.2	276	Deep wells
Joliet, Ill.	447	35.6	26.6	18.3	3.23		349	Deep wells
Kewanee, Ill.	123	.....	.....	17.9	3.43		445	Deep wells
Pueblo, Colo.	614	.....	.....	10.6	4.12 } 4.16	0.5-0.9 { 0.6	302	Arkansas River
Elgin, Ill.	403	21.2	33.2	11.4	4.44		103	Deep wells
Marion, Ohio	263	.....	.....	5.7	5.56		209	Deep wells
Lima, Ohio	454	.....	.....	2.2	6.52		223	Surface, impounded
Evanston, Ill.	256	15.4	41.8	3.9	6.73		131	Lake Michigan
Middletown, Ohio	370	.....	.....	1.9	7.03		329	Deep and shallow wells
Quincy, Ill.	330	.....	.....	2.4	7.06		88	Mississippi River
Oak Park, Ill.	329	18.2	43.8	4.3	7.22 } 7.40	< 0.5 { 0.0	132	Lake Michigan
Zanesville, Ohio	459	.....		2.6	7.33		291	Deep wells
Portsmouth, Ohio	469	.....	.....	1.3	7.72		80	Ohio River
Waukegan, Ill.	423	14.9	54.6	3.1	8.10		134	Lake Michigan
Elkhart, Ind.	278	.....	.....	1.4	8.23		220	Deep wells
Michigan City, Ind.	236	.....	.....	0.0	10.37		141	Lake Michigan

[1] Estimations made only on children of eight suburban-Chicago communities.

[Compiled from Dean, H. T., Jay, Philip, Arnold, F. A., Jr., and Elvove, E.: *Pub. Health Rep., 56:* 761-792, (Apr. 11) 1941; and Dean, H. T., Arnold, F. A., Jr., and Elvove E.: *Pub. Health Rep., 57:* 1155-1179, (Aug. 7) 1942.]

already erupted; the duration of the protective effects; the significance of topical application of concentrated fluoride solutions; and non-dental effects of prolonged ingestion trace amounts of fluorine. The answers to many of these questions are being sought in the newer studies on fluorine.

Relocation Experience (In Children): During the course of routine dental examination of persons of Japanese ancestry residing in War Relocation Authority centers, two groups of children at two different centers were examined in the summer of 1943 and again in 1945. Early in 1942 both groups, because of their Japanese ancestry, had been transferred from homes in or near Los Angeles to a nearby assembly center. Late in 1942 they were again transferred, 120 to a center in California and 196 to Arizona. The children relocated to California consumed fluoride-free water. The children in Arizona consumed deep well water containing 3 p.p.m. of fluorine (except during a 3-month period when fluorine-free water could be obtained, if desired, at several selected water outlets.*) During the two-year interval, 1943-1945, the children were restricted by military regulations to their respective centers. Their diets were adequate and, generally, quite similar.

At the time of the first examination in 1943 all of the children were quite similar with regard to the number of caries-free teeth in the mouth. The boys and girls destined to reside in the fluoride area averaged 13.4 and 14.7 caries-free permanent teeth, respectively, and the boys and girls in the control area, 12.8 and 14.1. After a 2-year residence in their respective areas a marked difference was observed in the number of teeth newly attacked by caries. The differences were particularly marked in the younger children. Children who were 8-10 years of age in 1943 were protected more in the subsequent two-year period of residence in the fluoride area than were children who had been 12-14 years of age at the beginning of the exposure. In the younger group, new caries attack was about 60 per cent less in the fluoride area than in the control area. This indicated not only that fluorine inhibits the development of new caries, but that the more recent the eruption of the tooth when exposure to fluorine is begun, the greater is the degree of protection against caries. (19).

In 1946, Klein (20) reported additional data derived from the preceding study which sheds further light on the question of fluoride protection in relation to the period of tooth eruption. In this later study, the following factors were studied: The effect of trace amounts of fluorine in the drinking water on the incidence of new teeth which have the highest caries suscep-

*Because of the high fluorine content of the water, the Relocation Authority attempted to remove the fluorides. Bone-meal filters were installed only at selected water outlets to which the public had to travel if they wanted fluorine-free water. Also bottled fluorine-free water was sold for use in infant formulas. Filtration of the water was discontinued after three months.

tibility (namely, the first and second molars and the second bicuspids [21]); the differential caries-inhibiting effects of such water on teeth when (a) already present in the mouth at the beginning of exposure and (b) not present in the mouth at the beginning but erupting during fluorine exposure. Examination of the children after two years of exposure (1943-1945) to fluorine showed a significant degree of protection against caries in first and second molars and second bicuspids already erupted provided exposure to fluorine began soon after eruption. It was further observed that even greater protection occurred in the same teeth (second molars and second bicuspids) exposed during the period of eruption.

Relocation Experience (In Adults): In studies of a somewhat similar, but not identical nature, Deatherage (21, 22) likewise obtained data further supporting the fluorine-dental caries hypothesis. In one survey, 2026 selective service men were given dental examinations and grouped into three broad divisions based on the nature of the domestic waters used (21). These were grouped as *fluoride-free* (from 0.0 to 0.1 p.p.m. of F), *suboptimal fluoride* (0.5 to 0.9 p.p.m. of F) and *fluoride* (1.0 p.p.m. and over). Individuals were classified according to whether they had used the domestic water in question (a) during their entire life, or (b) during the first eight years of life only (the period of dental calcification). A lower dental caries experience and a higher rate of teeth with no caries experience was observed in those using either type of fluoride water when compared with those using fluoride-free waters. The higher fluoride waters (1.0 p.p.m. or over) were associated with lowest dental caries experience.

In a subsequent survey, Deatherage (22) obtained data which substantiated these findings and indicated further that fluorine has an inhibitory effect on dental caries even after calcification of the permanent teeth. This latter finding, however, is in direct contrast with the majority of studies which indicate that the caries-inhibiting effect of fluorine is exerted only prior to completion of the calcification process.

Artificial Fluorination Studies: Inspired by the encouraging observations of dental caries inhibition in areas where the natural water supply provides fluorine in concentrations of 1 p.p.m. or more, a number of large-scale experiments were begun about 1944-1945 to determine whether artificially fluorinated water would confer similar protection. Thus far the following cities are participating: Grand Rapids, Michigan; Newburgh, New York; Midland, Michigan; Brantford, Ontario; Sheboygan, Wisconsin; Ottawa, Kansas; Evanston, Illinois and Marshall, Texas.

Preliminary reports on the reduction of L. *acidophilus* counts among Newburgh children have already appeared, indicating the favorable course

of the fluorine experiment in this community (23). On the basis of the demonstration that there is a direct correlation between the number of L. *acidophilus* organisms in the saliva and dental caries activity (24), L. *acidophilus* counts were used as one criterion of the effect of adding fluorine to the water supply. In Newburgh (on artificially fluorinated water since 1945), individual L. *acidophilus* counts were made on random samples of the school population in 1944, 1946 and 1947. The school population of the control city, Kingston (on fluorine-free water) was sampled in 1946 and 1947.

Samples of saliva from 244 children in Newburgh late in 1944 (prior to fluorination of water supply) showed 11.9 per cent negative (under 100 bacteria per cubic centimeter of saliva) and 63.5 per cent high (over 20,000 bacteria per cc.).* Analyses of 403 children in the same community early in 1946 showed an increase to 15.4 per cent negatives and a decrease from 63.5 to 55.2 per cent high counts. By 1947, analyses of 421 samples showed the negative percentage had risen to 20 per cent, while only 47.3 per cent had high counts.

Analyses of saliva samples of 402 in the control city of Kingston early in 1946 revealed 16.2 per cent had negative counts and 54.2 per cent had high counts.* In 1947, among 408 children in Kingston, the percentage of negative counts remained at 16.2 per cent and the high counts totaled 53.9 per cent—nearly identical with the previous year, and thus showing a constancy of bacterial conditions.

These preliminary data already show that whereas L. *acidophilus* counts, and consequently carious activity, remained relatively constant in an untreated area, a definite increase in negative counts (from 11.9 to 20 per cent) and a definite decrease in high counts (from 63.5 to 47.3 percent) has been experienced within a two-year period in a community whose water supply has been treated with fluorine to bring it to a level of 1 p.p.m.

Although this report constitutes only a preliminary observation in a 10-year experiment, it is, as the authors point out, the direction which would be expected if artificial fluorination ultimately produces a decrease in dental caries. An interesting comparison may be made between the distribution of low and high lactobacillus counts at Newburgh with the distribution in areas where fluorides occur naturally in the drinking water. Dean *et al* (15) in 1941 reported that in fluoride areas 37.4 per cent of the 12 to 14 year old children had negative lactobacillus counts and only 27.5 per cent of the same population group had very high counts. While the

*Studies conducted by Jay (24a) among representative population groups reveal that approximately 15 per cent of the individuals sampled have negative counts and about 57 per cent have significantly high counts.

differences between 1944 and 1947 data at Newburgh are statistically significant, the reduction in percentage of high lactobacillus counts and increased percentage of negative counts do not approach the figures reported for natural fluoride areas. As has been pointed out, the short duration of the Newburgh experiment and the fact that the counts at Newburgh were on school children would indicate that any differences observed were largely related to postdevelopmental effects and not to developmental influences of the increased fluoride ingestion (25).

Mechanism of Fluorine Behavior:

The mechanism whereby fluorine is effective in reducing the incidence of dental caries is still unknown. Numerous investigations on rats, hamsters and other animals, combined with observations on human beings have led to the propounding of many theories explaining the fluorine-dental caries hypothesis. These theories, summarized in an early issue of this Review, have been analyzed in detail on the basis of existing biological, chemical and epidemiological evidence by Hodge and Sognnaes (26). In an attempt to correlate the diverse existing facts, they have set forth the following hypothesis describing the possible mechanism of fluoride action:

> "Fluoride is adsorbed or bound in combination in enamel or in dentin, on the surface of the tooth, thereby,
>
> (1) lowering the solubility of the calcified part;
> (2) giving a relatively high local concentration of fluoride which inhibits those bacterial or enzymatic processes that otherwise are believed to dissolve the protein and the calcified material;
> (3) changing the salivary milieu as shown by lower L. *acidophilus* counts."

Is Fluorine a Dietary Essential?

In the foreword to the second volume on the fluorine-dental caries relationship to be published within a four-year period, Kitchen and Moulton (27) state,

> "Evidence has increased . . . that fluorides in limited amounts occurring naturally in domestic water supplies and food during the period of the development of permanent teeth of children do inhibit tooth decay . . . The evidence is now sufficient to raise high hopes for the future. These volumes have been published to make the evidence readily available not only to those who are specialists in dental science but also to others who are interested in nutrition."

Wherein does fluorine merit the interest of the nutritionist? It has not been established that fluorine is nutritionally indispensable nor that dental caries is a direct manifestation of fluorine deficiency. It has even been suggested that fluorination be considered a pharmacological approach to caries prevention rather than a physiological one (28). Nevertheless when it is

recommended that a substance be incorporated in the daily diet in trace amounts for a period of from eight to twelve years during the most critical years of life—the formative years—such a substance naturally becomes the concern of the nutritionist.

Fluorine Metabolism: Although the role of trace amounts of fluorine in maintaining the integrity of the teeth has been clearly demonstrated, very little is known concerning the metabolism of this element in the body. It has been demonstrated that the intensity of harmful effects of fluorine on bone and dental tissue is directly related to the quantity of fluorine which they retain. Recent evidence derived from fluorine balance studies by Machle *et al,* McClure *et al* and others (29) has shown, however, that there is a very efficient elimination of fluorine in man by way of the urine, and also some loss via perspiration. Results of such studies are strongly indicative that quantities of fluorine up to 3.0 to 4.0 mg. daily are perhaps more than 90 per cent eliminated by the average adult. Animal experiments indicate, however, that appreciable quantities of fluorine are retained in the growing young (30, 31) and this may have some bearing on fluorine metabolism in the human child. However, it has been clearly shown that the amount of fluorine ingested from waters containing fluorine in concentrations of 1.0 p.p.m. or less are far below the amounts producing adverse toxic effects.

Fluorine Availability from Food and Water: McClure (32) has demonstrated experimentally that the caries-inhibiting effect of fluorine is obtained whether the source of fluorine is food or water. Almost all foods contain traces of fluorine, but with the exception of certain teas and fish, and perhaps, milk, they constitute negligible sources of this element (Table II). Using Adolph's method (33) of determining the daily water requirement as 1 cc. per calorie of energy in the daily diet, McClure (34) has estimated that when the drinking water contains 1 p.p.m. of fluorine and the solid (dry) substance of the food contains from 0.1 to 1.0 p.p.m. of fluorine, the total fluorine intake for children from the age of 1 to 12 years would range from about 0.4 to 1.7 mg. per day.

Physiological Role of Fluorine: The large-scale experiments on fluorination of communal water supplies will contribute further to existing information on the physiological role of fluorine in the human body. In Newburgh, for example, annual dental examination of all 5 to 12 year old school children will be supplemented by detailed periodic pediatric examinations on a group of 500 children equally distributed as to sex ranging in age from birth to 12 years (35). Special attention will be given to physical and mental develop-

TABLE II.

FLUORINE CONTENT OF FOODS AS REPORTED IN THE LITERATURE*

Food	Fluorine, parts per million	Food	Fluorine, parts per million
Fluorine reported in food as consumed			
Milk	0.07–0.22	Pork chop	1.00
Egg white	0.00–0.60	Frankfurters	1.70
Egg yolk	0.40–2.00	Round steak	1.30
Butter	1.50	Oysters	1.50
Cheese	1.60	Herring (smoked)	3.50
Beef	< 0.20	Canned shrimp	4.40
Liver	1.50–1.60	Canned sardines	7.30–12.50
Veal	0.20	Canned salmon	8.50– 9.00
Mutton	< 0.20	Fresh fish	1.60– 7.00
Chicken	1.40	Canned mackerel	26.89†
Pork	< 0.20		
Fluorine reported in dry substance of food			
Rice	< 1.00	Honey	1.00
Corn	< 1.00	Cocoa	0.50– 2.00
Corn (canned)	< 0.20	Milk chocolate	0.50– 2.00
Oats	1.30	Chocolate (plain)	0.50
Crushed oats	< 0.20	Tea (various brands)	30.00–60.00
Dried beans	0.20	Cabbage	0.31– 0.50
Whole buckwheat	1.70	Lettuce	0.60– 0.80
Wheat bran	< 1.00	Spinach	1.00
Whole wheat flour	1.30	Tomatoes	0.60– 0.90
Biscuit flour	0.00	Turnips	< 0.20
Flour	1.10–1.20	Carrots	< 0.20
White bread	1.00	Potato (white)	< 0.20
Ginger biscuits	2.00	Potato (sweet)	< 0.20
Rye bread	5.30	Apples	0.80
Gelatin	0.00	Pineapple (canned)	0.00
Dextrose	0.50	Orange	0.22

*For the source of these analytic data see McClure (32).

ment and emotional stability. Complete physical examinations will also include checks on alertness, fatigability and irritability. X-ray studies of the bones and centers of ossification and blood and urine analyses will supplement the physical examinations. Similar examinations will be conducted in the control city, Kingston.

Adult examinations will determine the effects, if any, of trace amounts of fluorine on older age groups (past 50 years). Physical examinations, X-ray and laboratory tests will be made regularly on a group of 150 adults over 50 years, equally distributed as to sex in both Newburgh and Kingston.

When all of the data from these large scale tests become available it will be possible to fully evaluate the dietary role of fluorine, not only with respect to its influence on dental health but also in relation to its complete pharmacological-physiological behavior in the body.

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